A comparison of computational simulation and physical measurement of solar radiation and Photovoltaic outputs for residential dwellings

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Abstract

By 2016, new residential buildings in the UK will have to be 'net zero carbon' to comply with proposed changes to Part L of the Government's Building Regulations. Approved document Part L of the Building Regulations requires energy use and generation, and the resulting carbon emissions, to be quantified using the Government's Standard Assessment Procedure (SAP) model. To achieve a zero carbon dwelling, on-site renewable technologies must usually be incorporated into the design. Since the introduction of the Feed-In Tariff (FIT), in April 2010, photovoltaic (PV) systems have been seen as one of the most cost effective methods of achieving the higher levels of the Code for Sustainable Homes (CfSH), the route to meet zero carbon emissions in domestic buildings. The quantification of energy generation for CfSH certification, comes directly from the SAP model, where the methodology used to justify the use of PV systems is crude in its prediction of shading and utilises simplified rules-of-thumb to predict how shading will affect energy generation. This paper compares the prediction methods currently available to designers (SAP) against real data collected on live building projects in South West London. Included in this study is the physical measurement of solar radiation where PV panels will be installed at a later date, together with the measured outputs from two recent domestic PV installations that are benefiting from the FIT initiative. For both of these, in terms of solar radiation and electricity production, comparisons are made between actual measurements and predicted results. The results of this study show that the methodology provided in the SAP 2005 and 2009 models for determining the available energy at inverter output (kWh/year) for solar PV systems is crude and inaccurate, particularly in locations where there is significant shading from external obstructions, and particularly where an evaluation of the overshading is required. The SAP methodology for quantifying the shading coefficient is crude and there are little guideline provided. A novel technique for quantifying overshading has been tested in this study and the results indicate that a more robust method is required. The methodology being proposed is in line with more comprehensive approaches that have been adopted by other organisations, in particular new guidelines and methodologies published and recommended by the Microgeneration Certification Scheme (MCS). Proposals by the BRE for improvements to the SAP 2012 model, for the calculation of incident solar radiation, and the energy generated by a solar PV system, are generally positive but the determination of overshading in any particular location remains crude and difficult to quantify.

Keywords

Solar radiation; photovoltaic; shading; Building Regulations; SAP; sustainability.

1.0 Introduction

In 2007, the UK Government set, and has subsequently maintained, an ambitious target of ensuring all new homes will be net carbon neutral by 2016 (DCLG 2013). The route to achieve this is through the Code for Sustainable Homes (DCLG 2010), which categorises sustainability into nine broad areas; energy and carbon dioxide emissions; water; materials; surface water run-off; waste; pollution; health and Well Being; management; and ecology. To achieve the highest level, and the status of 'zero carbon', the net carbon emissions must be zero. The definition of a zero carbon building has been disputed for some time. When the Code for Sustainable Homes was first published in 2006, 'zero carbon' homes were defined as those where all CO_2 emissions were mitigated on site or by directly connected infrastructure. Subsequently, and after some debate, it became apparent that mitigating all CO_2 emissions on site would not be practically achievable for the vast majority of new dwellings. In 2008 the Government redefined 'zero carbon' homes as those where a hierarchical approach should be adopted as follows (Zero Carbon Hub 2009):

1. Ensure an energy efficient approach to building design
2. Reduced CO_2 emissions on-site via low and zero carbon technologies
3. Mitigate the remaining carbon emissions with a selection of 'allowable solutions'

In reality, the real energy consumption, and carbon emissions, in a dwelling are likely to be more than that predicted by the SAP model (BRE 2010), and alternative systems, such as the National Home Energy Rating (NHER) system developed by National Energy Services (NES 2013), account for these unregulated emissions, and indicate that they can be a significant proportion of the total energy consumed, and carbon emissions produced, in a typical dwelling. In 2009, the Housing Minister announced that the 'carbon compliance level would be set at a 70% reduction in regulated [that predicted by the SAP model] CO_2 emissions' (Zero Carbon Hub 2009).

The method used for calculating a building's CO_2 emissions is that described in the Government's Standard Assessment Procedure (SAP) which utilizes basic building geometry to calculate heat losses, energy consumption and carbon emissions. A building will always consume a certain amount of electricity, so to achieve a zero carbon rating, this must be offset; most commonly with on-site renewables.

PV systems can currently benefit from a Government funded Feed-in-Tariff that pays the owner a tariff for every kWh that they generate, even if the owner then consumes that energy. Higher level tariffs are available if the owner sends excess energy back into the National Grid. In effect, the owner gets free energy and they are paid for generating it. For this reason, PV systems have been recognised as a cost effective way of meeting the higher levels of the CfSH. Since the introduction of the FIT system in April 2010, and up until December 2012, over 340,000 domestic registered FIT PV systems (representing 99% of all FIT domestic technologies) have been installed, with a generating capacity of over 1,100 MW and an average installation capacity of 3.2kW (Ownergy 2013a).

There exists a wide range of tariffs available, currently and historically, based upon the technology adopted, the size of the installation, and more recently, on whether installed on an existing occupied building, a new building or as a stand-alone system not attached to a building. For a PV system installed on a new building, and less than 4.0kW, the original generation tariff in April 2010 was 36.1p for each kWh generated and this figure has progressively been reduced to the current tariff (from April 2013) of 14.9p for each kWh generated. Additional export tariffs are available where the energy generated is sent back to the National Grid (Ownergy 2013b).

Just prior to this study being carried out, and towards the end of 2011 the UK Government attempted to reduce the tariff rates for solar PV significantly, with limited public consultation, but this was challenged and tested in the courts and was deemed to be unlawful to implement at that time. This delayed the onset of what was to become a considerable reduction in tariff which led to a significant increase in the number of domestic installations, caused by a general rush to install systems at the higher tariff rate.

Subsequently, and inevitably, in March 2012 the Government reduced the tariffs by approximately 50% which had an impact on the take-up of this technology in the domestic market.

This study evaluates the solar PV prediction methods currently available to designers (SAP) against real data collected on live building projects in South West London. It includes the physical measurement of solar radiation where PV panels will be installed at a later date, together with the measured outputs from two recent real domestic PV installations that are benefiting from the FIT initiative. Comparisons have been made between actual measurements and predicted results and the main focus of the study is the quantification of shading. A number of previous studies have examined the impact of shading on the performance of PV installations but the vast majority of these studies have examined the impact of shading on the performance of the PV modules themselves, and the resulting reduction in electrical output, rather than an assessment of the general impact of shading on incident solar radiation and the electrical output of individual domestic system installations (Alonso-Garcia et al 2006 and Woyte et al 2003). Work by Murphy et al (2009) evaluated the simulation of PV installations using the SAP 2005 model and concluded that whilst there is less scope for errors when compared to more detailed models such as PVSYST, specific PV system data cannot be modeled, nor can site location be specified which leads to the SAP model over-predicting PV output for all UK locations North of Sheffield, and under-predicting PV output for locations further South. It has been estimated that there could be a potential output difference of up to 35%.

2.0 Methodology

This study was designed to test the prediction of solar radiation and PV electrical outputs against real measured data. There were two key areas of investigation, the first being the physical measurement of solar radiation on a site where an energy efficient dwelling is being built which has significant shading from trees and surrounding buildings and has been designed with a large PV array installed horizontally on the roof. The second investigation examines the effectiveness of two completed PV installations and compares a year's worth of collected electrical energy data against the SAP predictions that were used originally to justify their installation. These two systems were registered for the Government's FIT initiative and so were installed by a Microgeneration Certification Scheme (MCS) accredited installer. The justification and eligibility of the systems under this initiative were determined using the SAP calculation methodology, which is a basic requirement under this scheme.

The measured solar radiation and electrical outputs in both investigations took place during the same one year period between September 2011 and October 2012. Both of these have also been compared to the predictions of solar radiation and electrical output that have been generated using the Government's standard protocol for determining solar radiation, using the current Standard Assessment Procedure (SAP) model (2009).

3.0 Prediction of solar irradiation using the SAP model

The Standard Assessment Procedure (SAP) is the Government's approved method for calculating a dwelling's energy consumption and carbon emissions. Both the earlier (2005) and current (2009) versions of SAP are relevant in this study because there exists a significant number of dwellings that were granted planning approval when the 2005 model was current in addition to those that have subsequently been approved in the 2009 version of the model. Both versions of SAP use a simple method of calculation to predict the energy output from PV installations although there are variations between the two versions. The available energy at inverter output (kWh/year) is determined using the following equation:

$$\mathbf{0.8 \times kWp \times S \times Z_{pv}}$$

Where the kWp is the installed peak power for the PV modules, S is the annual solar radiation (kWh/m^2) (depending on orientation and tilt), and Z_{PV} is the over-shading factor provided in Appendix H of the SAP documentation (BRE 2009, 2011a, 2014).

Table 1 shows the annual solar radiation data (S) that is used for these variables and indicates those values used in the SAP 2009 model together with those values *(in brackets)* that are used in the earlier SAP 2005 model. It is interesting to note that these solar radiation figures have increased by approximately 3% from the 2005 version of the SAP model and the 2009 version.

Tilt of collector	**Orientation of collector**				
	South	**SE/SW**	**E/W**	**NE/NW**	**North**
Horizontal	961 *(933)*				
30°	1073 *(1042)*	1027 *(997)*	913 *(886)*	785 *(762)*	730 *(709)*
45°	1054 *(1023)*	997 *(968)*	854 *(829)*	686 *(666)*	640 *(621)*
60°	989 *(960)*	927 *(900)*	776 *(753)*	597 *(580)*	500 *(485)*
Vertical	746 *(724)*	705 *(684)*	582 *(565)*	440 *(427)*	371 *(360)*

Table 1: Annual solar radiation, (S) kWh/m² (BRE 2009, 2011a)

In SAP 2005, the annual solar radiation figure from Table 1 is used in the calculation of annual energy output for the PV installation. In the current SAP 2009 model, the most significant development is the determination of monthly available energy output which is calculated using the data in Table 2. This shows the ratio of monthly solar radiation to annual averages for different collector tilts from horizontal through to vertical that are used in this calculation. In addition, the later SAP 2009 model allows more than one type of PV installation to be accounted for.

Tilt	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Sum**
Horiz	0.24	0.50	0.86	1.37	1.74	1.84	1.78	1.50	1.06	0.63	0.31	0.19	*12*
30°	0.35	0.63	0.92	1.30	1.58	1.68	1.62	1.39	1.08	0.74	0.43	0.29	*12*
45°	0.39	0.69	0.95	1.27	1.52	1.61	1.55	1.34	1.08	0.79	0.48	0.33	*12*
60°	0.44	0.74	0.97	1.24	1.45	1.54	1.48	1.30	1.09	0.84	0.53	0.37	*12*
Vert	0.58	0.92	1.05	1.15	1.25	1.33	1.28	1.15	1.10	0.99	0.69	0.50	*12*

Table 2: Ratio of monthly solar radiation to annual average solar radiation (BRE 2011a)

Table 3 shows the over-shading factors applied to the calculation and is the same in the SAP 2005 model and the SAP 2009 model.

Overshading	**% of sky blocked by obstacles**	**Overshading factor**
Heavy	> 80%	0.5
Significant	> 60% - 80%	0.65
Modest	20% - 60%	0.8
None or very little	< 20%	1.0
Note: Overshading must be assessed separately for solar panels, taking account of the tilt of the collector. Usually there is less overshading of a solar collector compared to overshading of windows for solar gain (Table 6d).		

Table 3: (SAP 2009) Overshading factor, (Zpv) (BRE 2009, 2011a)

Estimating and selecting an appropriate level of shading is clearly critical and has a significant impact on the resulting predictions of annual overshading. Despite numerous sources quoting this information, including the most recent SAP 2012 guidance documentation (BRE 2014), there is very limited advice on how to select an appropriate figure for the overshading factor. Quantifying the percentage of sky blocked by obstacles can only be estimated in most cases, where some shading exists. This is fundamentally important in this calculation since the appropriate selection of an overshading factor can change the predicted solar radiation by a factor of up to 2. It is also worth pointing out that the results from the SAP calculations are used as the basis for determining credits that are available from the current Code for Sustainable Homes (DCLG 2010), and for the calculation methodology adopted by the Government for Feed-in-Tariff payments.

Trees are often ignored in line with the guidance suggested as their shape is difficult to predict (Littlefair 2009). However, installing PV panels in heavily wooded areas can reduce direct solar gains, and therefore energy production, dramatically.

This study has evaluated two alternative methods for more accurately predicting the overshading factor; (a) taking panoramic images from the location and superimposing them onto a sunpath diagram for the relevant latitude, and (b) using draft MCS guidelines (MCS 2011) for quantifying overshading.

Figure 1 shows the predictions for a typical horizontal solar collector based on an annual solar radiation figure of 961kWh/m^2, and for each of the shading options provided in the SAP 2009 model.

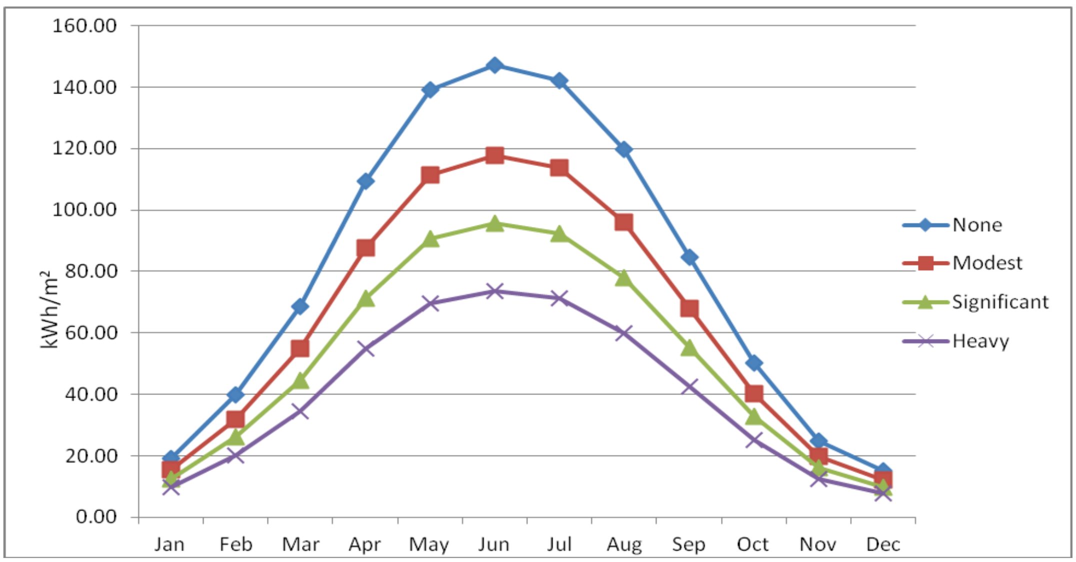

Figure 1: Monthly solar radiation (kWh/m^2) predicted by SAP 2009 for a horizontal solar collector under the four standard categories of shading

4.0 Measurement of solar radiation and PV output

This section describes the two case study investigations: (a) case study 1, where solar radiation was measured at three locations on a site where a significant solar PV installation is being planned, and (b) case study 2, where electrical output was measured at two new domestic solar PV installations benefiting from the Government's FIT initiative.

4.1 Case Study 1: Measurement of solar radiation

This part of the study relates to the design and construction of a CfSH Level 5 domestic dwelling, in Teddington. The dwelling comprises 400 m^2 of floor area over three levels including a basement, ground floor and first, is highly insulated, airtight and energy efficient. In order to achieve CfSH Level 5 the dwelling design incorporates 70m^2 of photovoltaic panels, installed horizontally on the roof of the building with an installed capacity of 12.0kW$_p$.

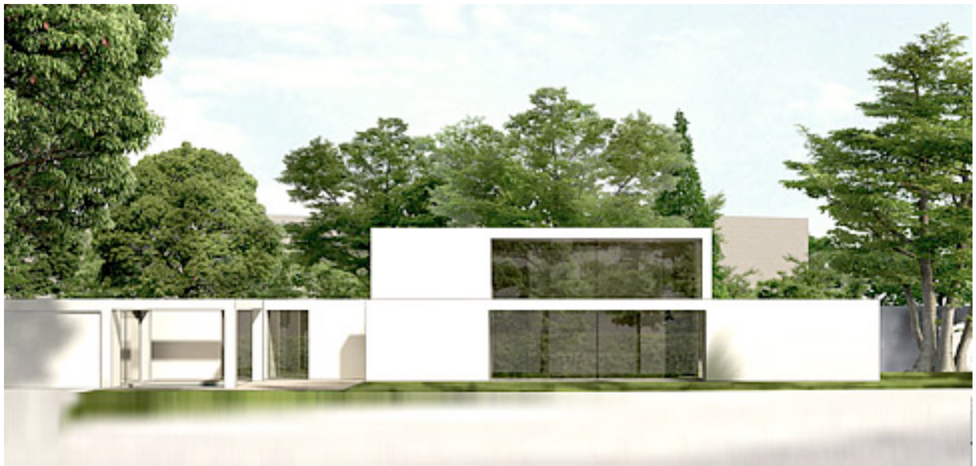

Figure 2: Architectural visualisation of Case Study 1

At a very early stage in the design process an assessment was carried out, using Autodesk Ecotect (Autodesk 2010), on the incidence of solar radiation on the roof area of the building in order to evaluate the effectiveness and location of the panels being proposed. Figure 3 shows the results of this assessment and indicates that there is some variability in the predicted solar radiation across the roof area.

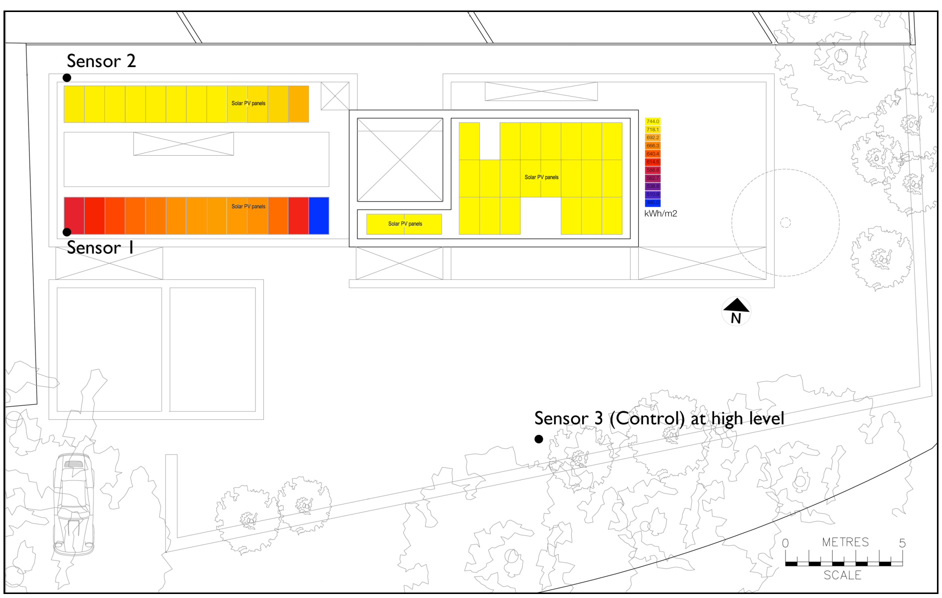

Figure 3: predicted annual radiation (kWh/m^2) on the roof of Case Study 1

The Ecotect predictions of the relative incidence of radiation on various parts of the roof were then used to determine the most appropriate locations to set up solar irradiance sensors and datalogging equipment in order to measure solar radiation for a whole year. The monitoring equipment used for this study was provided by Omni Instruments (Omni 2011) and included three SP-Lite pyranometers for measuring solar radiation connected to an RME1 analogue Ethernet I/P module with internal memory and battery backup, with data retrieval via a secure website and with online graphing and data analysis.

As shown in Figure 3, of the three sensors being used, Sensor 3 was positioned as high as possible in the centre of the site representing the control (most unshaded location) and the other two, Sensors 1 and 2, were positioned in two locations relevant to the position of the roof of the proposed building so that they were measuring incident solar radiation at appropriate positions and accounted for surrounding shading. At each of these three locations, the incident solar radiation was measured every 15 minutes and the data was collected for a whole year for the period September 2011 to August 2012.

Each sensor took a reading of the solar radiation being received (W/m^2) every 15 minutes and this data was downloaded each month and modified to units of kWh/m^2.

Table 4 shows the average monthly solar radiation (kWh/m^2) measured at each of the three sensor locations, September 2011 to August 2012. Figure 4 also shows this data graphically.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	**Total**
S 1	9.2	28.4	37.5	50.0	66.4	61.9	70.2	61.0	42.0	26.4	14.2	10.5	**477.8**
S 2	10.3	30.2	48.4	63.9	97.1	82.1	93.3	78.9	53.5	30.5	16.2	12.3	**616.6**
S 3 (c)	12.9	30.5	58.1	89.1	126.3	106.5	124.3	102.6	71.0	42.6	20.1	14.8	**798.8**

Table 4: Average monthly solar radiation (kWh/m2) at each sensor location

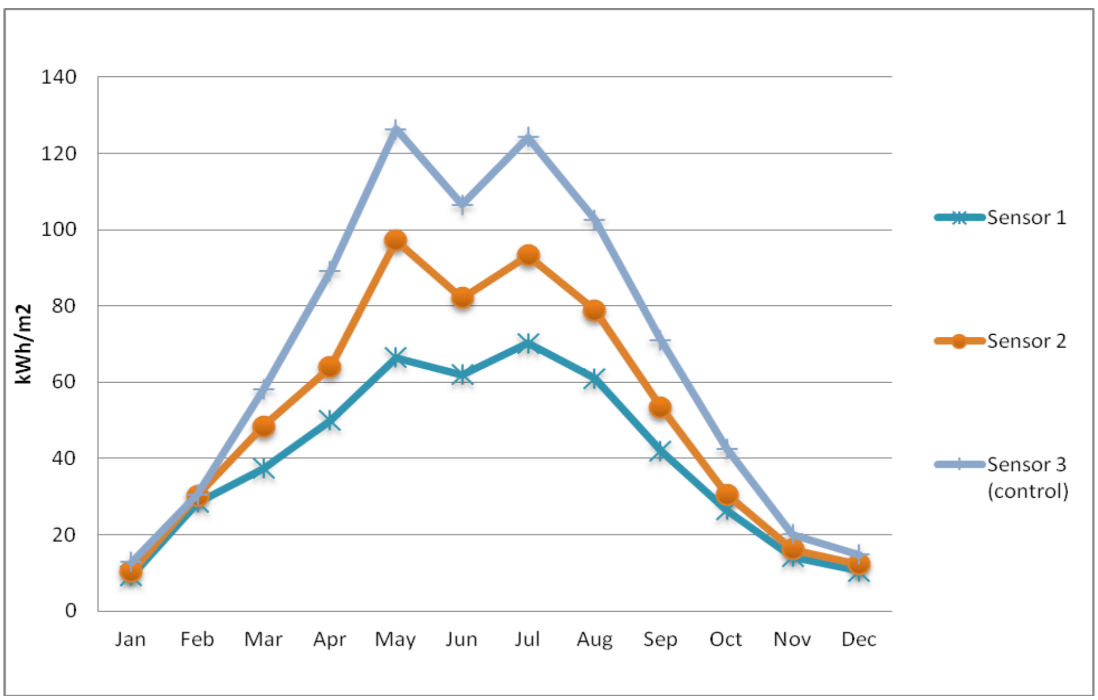

Figure 4: average monthly horizontal solar radiation (kWh/m^2) at case study 1

It is clear from the data collected that there was a significant reduction in the available solar radiation during the month of June 2012. Other reliable sources of solar radiation data, from Heathrow, UK, (Met Office 2014) during this period were evaluated and showed similar trends in this geographical location.

4.2 Case Study 2: measurement of electrical output from solar PV installations

Two domestic solar PV systems, installed under the Government's Feed-In-Tariff (FIT) initiative have been investigated in this study. They were installed by a recently accredited MCS installer who justified the installation in terms of installed load, costs and payback periods in line with the guidelines published by MCS at the time.

The first system, Dwelling 1, relates to the design, supply, installation and commissioning of a 2.25 kW_p PV system in Epsom, incorporating nine Sanyo HIT H series 250W PV panels with a Fronius IG20 2.0kW inverter system.

The PV panels were installed at an inclination of 30° and were predominantly south facing in orientation. An on-site assessment of shading at this height and location led to the installation being classified as 'none or very little', using the methodology described in the SAP 2009 model documentation.

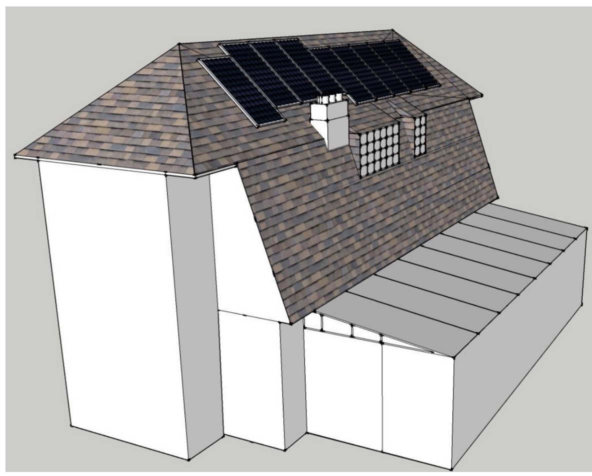

Figure 5: Dwelling 1 representation of the PV installation

The second PV system, Dwelling 2, was installed horizontally on the rooftop of a dwelling, comprising a 2.88 kW_p system, installed horizontally and incorporating twelve UpSolar 240W Poly panels with a Fronius IG30 2.6kW inverter. On site assessments of shading at the height of the installation led to a classification of 'none or very little' shading as described by the SAP 2009 model.

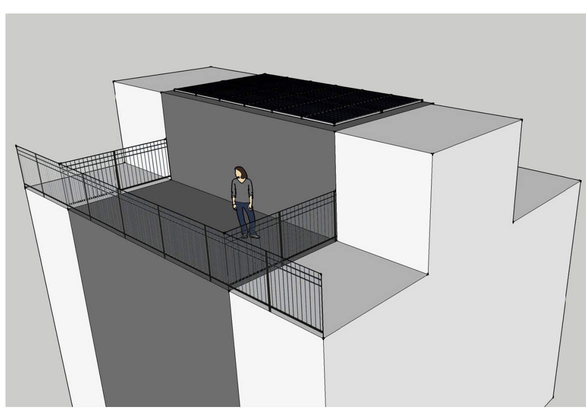

Figure 6: Dwelling 2 representation of the PV installations

During the period of monitoring the output electrical energy was measured for both of the solar PV installations and the results are shown in Table 5 and Figure 7.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
D1	39.6	108.9	142.4	200.8	286.9	266.2	305.7	257.6	184.2	110.2	55.9	45.8
D2	32.0	88.1	164.8	232.4	332.0	332.7	382.0	321.9	170.7	102.1	51.8	37.1

Table 5: Measured electrical outputs from the two PV installations

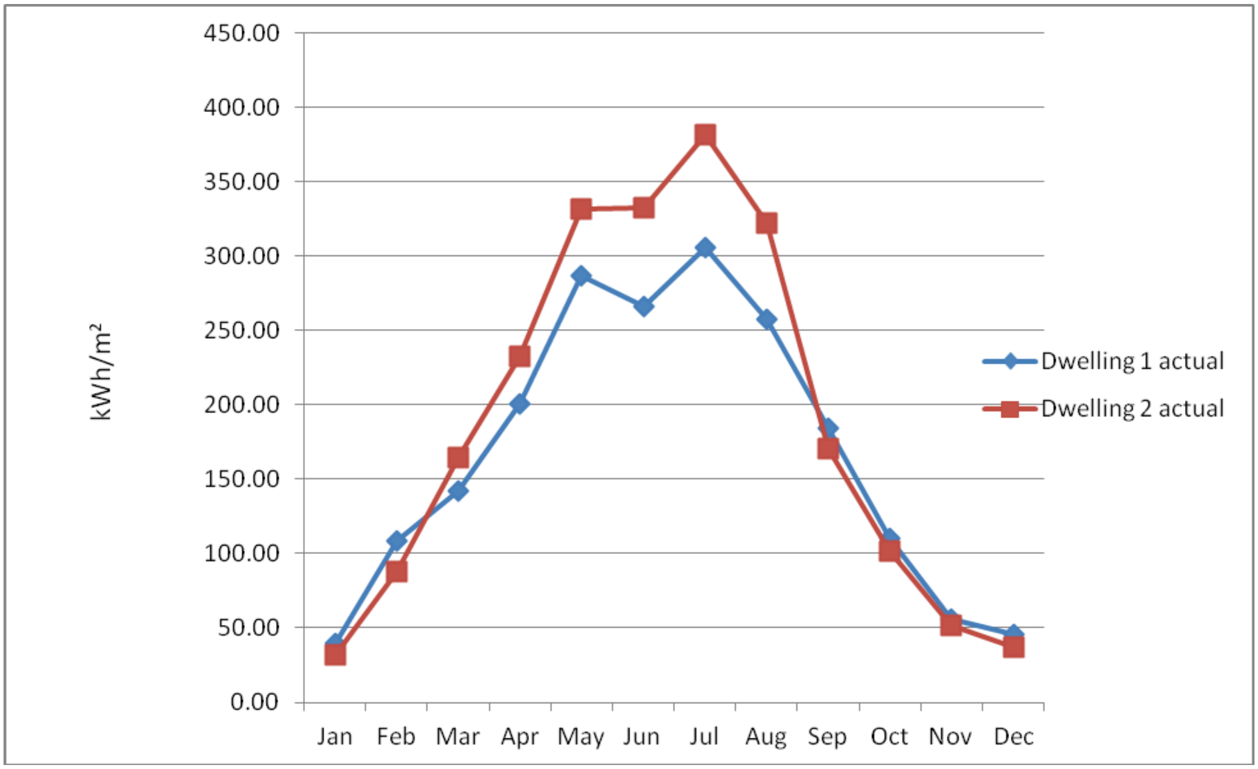

Figure 7: measured electrical outputs from the two PV installations

It is interesting to note that in this location there was a reduction in measured PV output during the month of June 2012 which coincides with the reduction in the measured solar radiation from Case Study 1 during the same period, and the Heathrow meteorological data.

5.0 Comparison of measured and predicted results

This section compares the SAP model predictions of solar radiation with measurements for both the case study sites

5.1 Case study 1

In order to estimate the overshading factor (Zpv) for each of the three sensor locations for case study 1, the SAP methodology was used. SAP provides this information (see Table 3), but, as previously discussed, there are very limited guidelines on how the overshading factors can be determined because it is difficult to quantify the percentage of the sky which is blocked by obstacles, as required.

In this study, to determine overshading factors, a novel method was tested which superimposed a panoramic (fisheye) image of the sky into stereographic sunpath diagrams, for each of the three sensor locations, for the latitude of 51°N generated using Autodesk Ecotect's Solar Tool (Autodesk 2010). This allowed the visible percentage of the sunpath to be determined for each of the sensors with a reasonable degree of accuracy. In each of the sensor locations, the vast majority of the shaded areas are represented by evergreen trees. Figure 8 shows the panoramic sky image for sensor 3 (control) superimposed onto the sunpath diagram. This was used to determine the percentage of the sunpath which was shaded, which in turn was used to select an appropriate overshading factor for the SAP calculation.

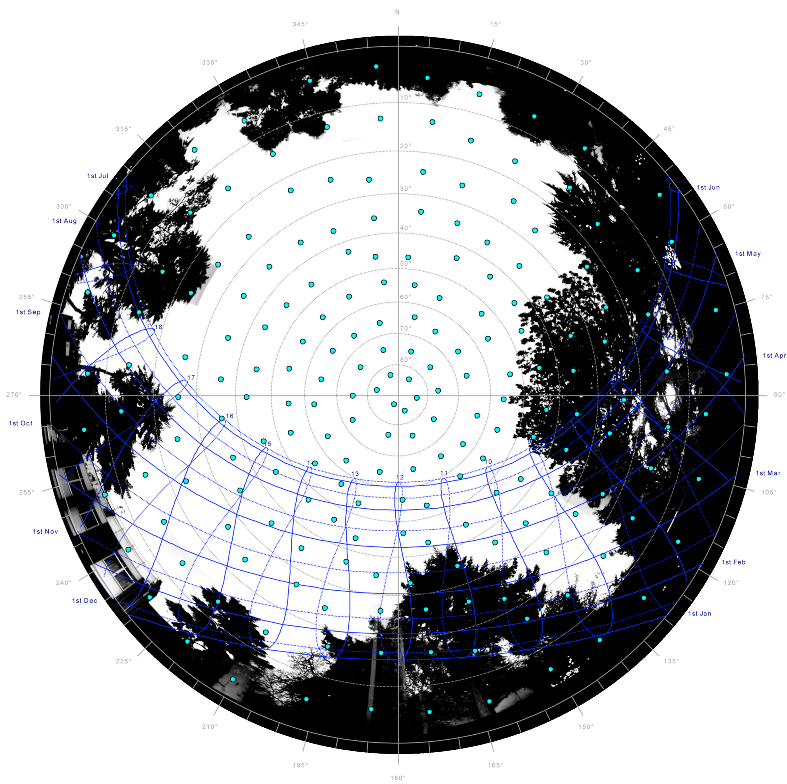

Figure 8: panoramic image of visible sky from sensor 3 (control)

A similar image was generated for all three of the sensor locations on site, and Table 6, shows the results of the determination of appropriate overshading factors for each location.

Location	Sunpath shaded dots (out of maximum of55)	Percentage of sunpath shaded (%)	SAP overshading classification, as shown in Table 3
Sensor 1	44	80	On the cusp of HEAVY and SIGNIFICANT shading (shading factor of 0.5 and 0.65)
Sensor 2	33	60	On the cusp of SIGNIFICANT and MODEST shading (shading factor of 0.65 and 0.8)
Sensor 3 (control)	18	33	MODEST (shading factor of 0.8)

Table 6: Overshading classifications for three sensor locations

It is important to differentiate between how much of the overall sky (direct and diffuse component) is shaded and how much of the sunpath area of the sky (direct component) is shaded. Guidelines published by the MCS (2011) show clearly that when assessing overshading factors only the sunpath area of the sky should be considered. It is also clear that the areas of the sunpath before 0800 and after 1400 should be ignored because the sun is insufficiently high in the sky to have an impact. Analysis of the panoramic sky images agree with this methodology. If the whole sky is used to quantify the percentage of the sky which is shaded, then the resulting overshading factors are underestimated resulting in predictions of solar incidence being overestimated by a significant degree.

The results in Table 6 also show that when quantified, the overshading factors for both sensors 1 and 2 sit right on the cusp of two different categories which leads to confusion about which category is most appropriate and could have a significant impact on the predictions of the available energy. This leads to the question of whether a more robust methodology for determining shading coefficients should be considered, particularly on sites where there is a lot of external shading from both surrounding buildings and evergreen trees.

Figure 9 shows the monitored and predicted results for case study 1. In comparing the measured and predicted data it is clear that in this study the measured conditions at sensors 1, 2 and 3 most appropriately fit overshading classifications of Heavy, Significant and Modest respectively as defined by the SAP model. However, although the trends for the predictions are a reasonable fit, had the sunlight levels not dipped in June, the predictions of energy generation appear slightly low. Whilst there is reasonable agreement between the measured and predicted overshading factors, it does not detract from the fact that for two of the sensor locations (1 and 2) the classification of shading sits on the cusp of two shading coefficients as defined by the SAP methodology, and in theory, either could have been adopted, resulting in potentially significant differences in predicted energy generation. Superimposing the panoramic image of the sky, onto the appropriate sunpath diagram results in an accurate quantification of the actual overshading coefficients (Zpv). This can then be applied to the fundamental equation for predicting solar irradiation in the SAP model.

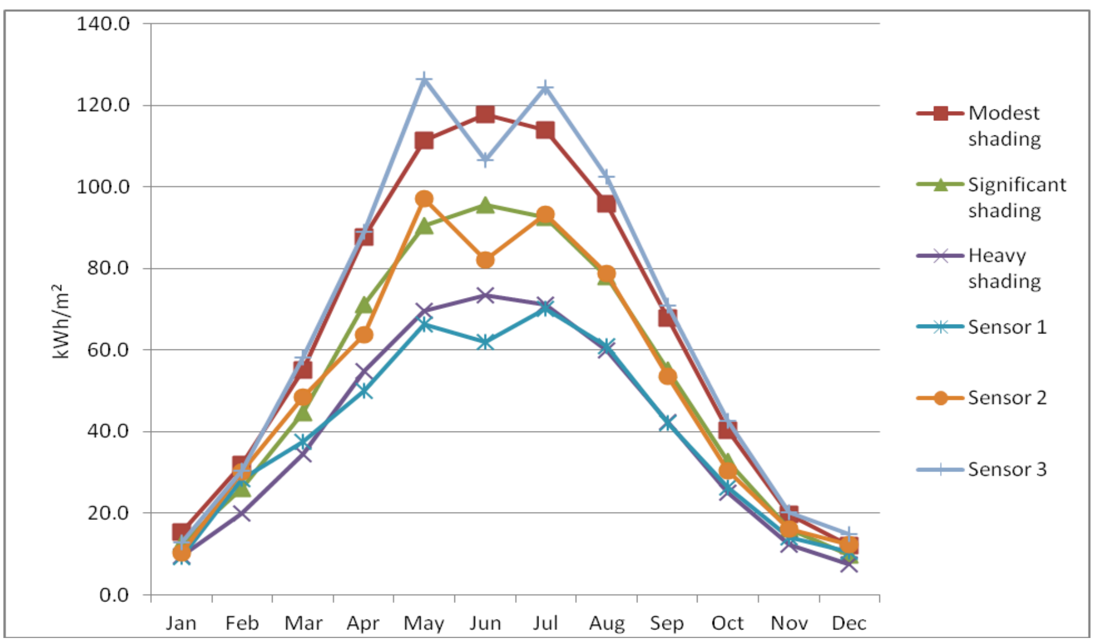

Figure 9: monitored and predicted results for case study 1

5.2 Case Study 2

The assumptions that were made for the overshading of the two Case Study 2 dwellings were described in section 4.2. In both cases the overshading on site was assessed as ‘none or very little’ and so the overshading factor in both cases was 1.0 (there was no reduction in PV output predicted as a result). Figure 10 below shows the measured and predicted electrical output (kWh/m^2) for the two dwellings

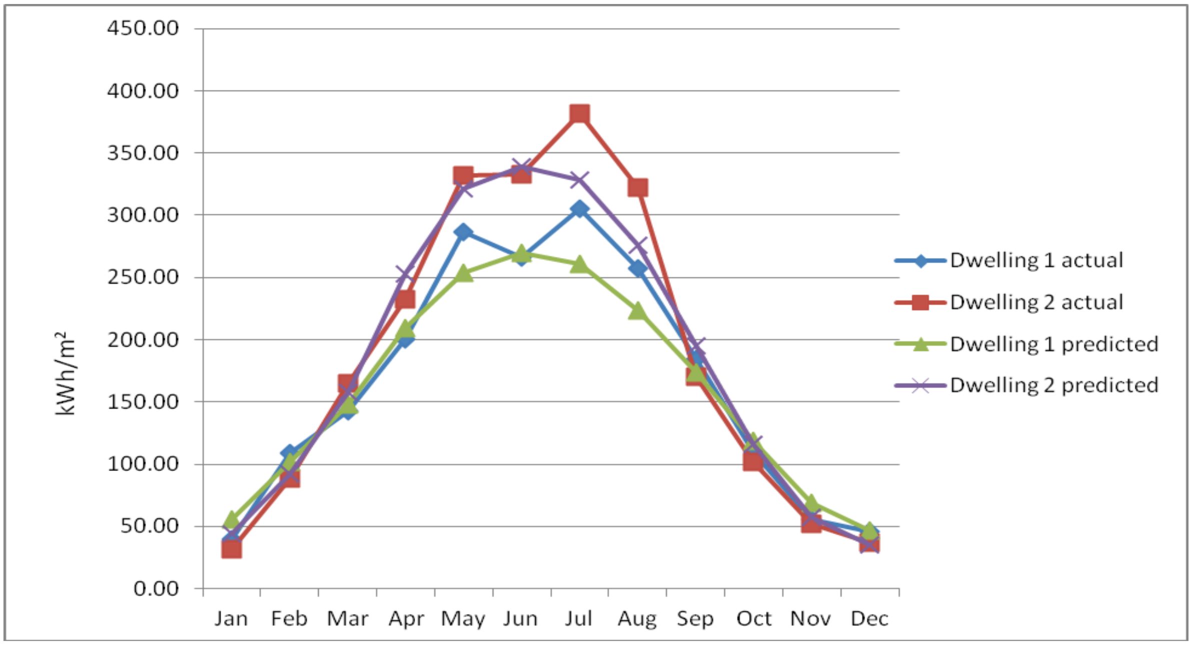

Figure 10: monitored and predicted data for the two PV installations

Whilst the overall trends for the predictions are a good fit, again, had the sunlight levels not dipped in June, the predictions of electrical generation appear low which is of particular concern since it was assumed that there was no overshading in the calculations.

6.0 MCS Guidelines for PV installations

For some considerable time there have been concerns regarding the predictions of electrical outputs from domestic solar PV installations. In July 2011, Which? (2013) investigated MCS accredited solar PV installers and found that eight out of twelve companies underestimated the time it would take for PV systems to pay for themselves. They also found that the majority of companies failed to take into account solar shading where it was obvious and where it would make panel installations questionable. As a result, the Microgeneration Certification Scheme (MCS) recently published comprehensive updated guidelines for registered installers (MCS 2012). These guidelines now include a revised methodology for quantifying PV system performance and a new system for estimating annual electricity generated which accounts for geographical location, PV array orientation and inclination to an accuracy of 5° and 1° respectively, and shading factors quantified using a sunpath diagram.

For shading factors, the MCS guidelines deal separately with situations where shading objects are up to 10m away and where they are further than 10m away from the array, although the basic methodology is similar. Figure 11 shows the sunpath diagram, published by the MCS, used for this purpose.

Fig 24

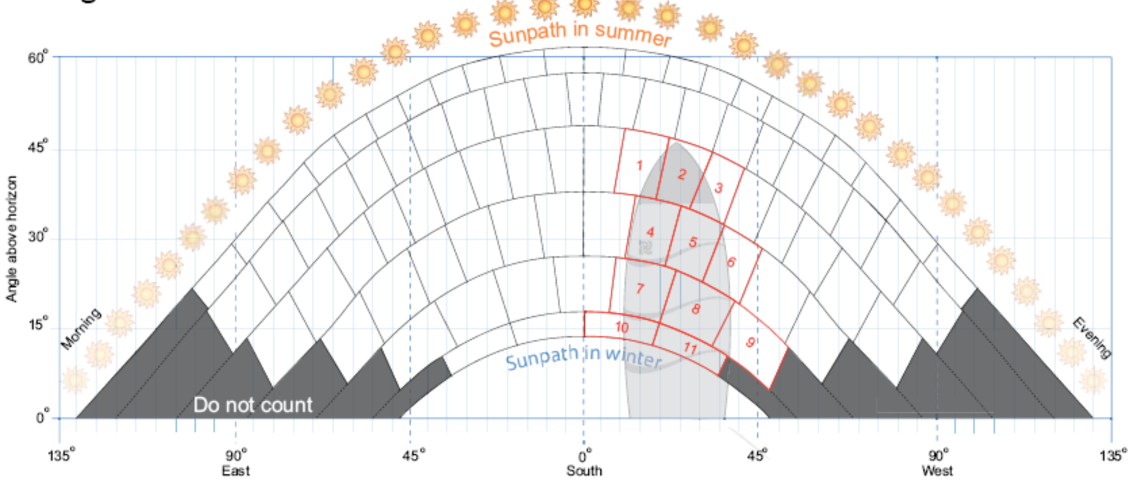

Figure 11: MCS guidelines for determining shading factors (MCS 2012)

The method described in the MCS guidelines require you to (a) stand as near as possible to the proposed location of the array, (b) looking due south draw a line showing the uppermost edge of any objects visible on the horizon onto the diagram, (c) count the number of segments that have been touched or are within the line (in this case 11 segments), (d) multiply the total number of affected segments by 0.01, and (e) deduct this from 1 to arrive at the shading factor.

In this case:

1 – (11 x 0.01) = 0.89

The methodology adopted in these new guidelines is a significant improvement, both on what has been previously published by the MCS and also on the crude methodology currently used in the SAP calculation. It is also similar to the novel approach which we have adopted in this study, in the sense that it requires a more comprehensive visual assessment at the location of the solar PV installation and with specific reference to the relative position of the sun. However there are a number of issues associated with the ease with which the MCS system can be applied. It is not clear how someone can position themselves (rather than a fisheye lens camera) easily at the specific location of a proposed PV array, particularly if the building has not yet been built. It is also not clear how the shading diagram is actually used in practice in terms of considering orientation and inclination of objects that could be some considerable distance away from the observer. It is worth also noting that the MCS guidelines make it very clear that this method is not intended to be as accurate as more sophisticated methods such as those used in software packages, but that it is estimated that this method will yield results within 10% of actual energy yield for most systems (MCS 2012).

A number of professional and commercial organisations have responded to the need for more accurate methods of determining solar shading, and produce a variety of tools, both physical and digital, that enable the shading coefficients to be measured on site with a greater level of accuracy. Simple tools are available in the market that provide visual systems incorporating solar acetates similar to that shown in Figure 11, and more complex systems, such as the Solar Pathfinder (www.solarpathfinder.com), are available which incorporates a transparent dome, positioned horizontally, which is then photographed from above, superimposing an image of the sky and shaded areas on a sunpath diagram which is positioned underneath. In addition, a number of more complex digital handheld tools are available, such as that developed by Solar Design (www.solardesign.co.uk), which incorporates a digital fisheye camera for quick and accurate assessments of shading in any location, similar to the novel technique used in this study, and described in section 5.1.

8.0 Conclusions and discussion

This study set out to investigate, and compare, various systems for predicting and measuring solar radiation and solar PV outputs for residential dwellings in the UK. As the UK Building Regulations move steadily towards the requirement for zero carbon homes, and since the introduction of the Government's Feed-In Tariff initiative, solar PV installations have been seen as one of the main methods for achieving this. In 2012, the UK Government stated that 4 million homes in the UK will be powered by the sun within eight years (Harvey 2012). At the moment, approximately 10% of this figure has been achieved, and with Feed-in Tariff rates progressively and regularly reducing since their introduction in 2010, this is looking like a target that is going to be difficult to meet.

The study evaluated the solar PV prediction methodology available to designers at that time; the Government's Standard Assessment Procedure (SAP 2009, 2011a), and has compared those predictions against real data collected on live projects in the South West London region of the UK. This has included the physical measurement of solar radiation on a site where a future solar PV installation is being planned and also the monitoring of the electrical output of two domestic solar PV installations compared to the predictions which justified and quantified their likely performance. Key to this study is the evaluation of shading from surrounding obstructions, including buildings and trees, and the comparison between assumptions that are made in predicting this shading and the reality of shading on site.

A considerable amount of monitoring took place during this project, including the measurement of solar radiation at a specific site and the measurement of electrical energy generation on another over one full year. Both of these datasets were then compared with the predictions of the standard models used to quantify solar radiation and electrical energy output. Most predictive models use standardized (theoretical and empirical) input data that has been developed over many years and it is possible that the measured conditions for this particular period is different to that incorporated into the predictive models. The study has identified some anomalies in the measured data but these have been compared to other weather station data collected by the Met Office locally and there is good agreement.

The SAP methodology and calculation for quantifying the available energy at inverter output (kWh/year) is relatively crude on a number of levels, although it is acknowledged that any increase in complexity of this methodology would risk it being used less by the designers who will make most use of it. The calculation assumes, in all cases, that there is a loss of 20% and it is not clear on what basis this figure is used, particularly with the advances in efficiency of solar PV electrical generation over the last few years. Predictions of the annual solar radiation (S) were also crude and increased by approximately 3% between the publication of the SAP 2005 and 2009 models. A technical paper published by the BRE in 2011 (BRE 2011b) set out proposed changes to the calculation of solar radiation (S) and in the SAP 2012 model (BRE 2014) the methodology has been significantly improved, and adopted, so that the calculation is capable of estimating the solar radiation for 'the applicable climate and orientation and tilt of the PV'.

The determination of the overshading coefficient (Zpv) has the most significant impact on predicting available energy at inverter output, and quantifying this for any solar PV installation has been the main focus of this study. This is acknowledged by Murphy et al (2009) who state 'further work is needed to assess the impact of shading. It is known that shading can have a devastating effect on PV performance, and it is unclear how the basic categories in SAP can address this'.

The first case study evaluated the available solar radiation on a site where a future solar PV installation was proposed. Solar radiation was monitored over a full year and this was compared to the predictions of the SAP model. Comparisons of the measured and predicted results show good agreement, but only where the appropriate SAP overshading classifications are assumed. For this case study, and for each of the three locations monitored, selecting an appropriate overshading classification from SAP was not straightforward and there was little guidance provided. As a result a novel technique was adopted, which more accurately quantified the percentage of the sunpath that was blocked by obstacles. This novel technique required superimposing a fisheye image of the sky from each location onto a sunpath diagram and quantifying the proportion of this that was shaded. Comparisons between this novel method and the SAP method showed that in two out of three cases the overshading was on the cusp of two SAP classifications which suggests there is significant scope for error and inaccuracy in the model predictions. Recently published guidance from the MCS includes a new methodology for quantifying overshading for solar PV installations and this development supports the findings of this study. It also implies that the SAP model is not currently sufficiently detailed enough to be used to support the installation of solar PV, particularly where there is significant, and quantifiable, external shading.

The second case study compared measured electrical output to SAP predicted outputs for two domestic solar PV installations. In both cases the installations were located in positions where the overshading was classified, correctly, as 'none or very little' and, therefore, the overshading issue was essentially removed from the analysis. In both dwellings the measured and predicted outputs show reasonable agreement, although the results suggest that even with 'none or very little' shading the predictions of electrical generation were slightly low compared to the measured outputs, particularly during the summer. It is not possible to say for sure whether this was caused by the SAP assumptions for PV system efficiency or for actual solar radiation during this period.

The study has shown that the current methodology used by the SAP models to determine electrical output of solar PV systems is, in significant areas, crude, that various input parameters are open to interpretation and there is potential for errors. The BRE have made some significant improvements in new and current version of the SAP 2012 model and these will account for regional variations in solar irradiance and improved calculations for PV outputs for any given orientation and tilt. However, no changes have been put in place for the determination of the overshading coefficient (Zpv), and the methodology for this remains as before, which is a lost opportunity.

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